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INVESTIGATION OF 10^{10} BIT OPTICAL MEMORY

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INTRODUCTION

This report covers the second phase of our work in the field of optical data storage and processing. The first phase laid the groundwork in terms of system design and component analysis; the second phase explored the properties of Bragg holography in alkali halide crystals. In order to present this work in the context of the broader perspective of the optical computer, we have included relevant excerpts from the first interim report, published October 1966.

A large number of extremely capable scientists have given their attention to this field, and therefore, many articles have appeared in the literature on this subject, especially in recent years. Several factors caused this renewed interest; the discovery of the laser, the ever-pressing need for larger computer memories, the discovery and development of new storage media (such as alkali halide crystals, photochromic materials) and the brilliant developments in holography.

These new developments would lead one to believe that optical computers far superior to any other kind, can be built in the near future. Four months ago we set out to examine scientifically what it is that an optical computer can do better than an electronic computer, and to determine whether the presently available technology is sufficient to build such an optical computer. During our study we aimed to determine the critical problem areas and to provide at least partial solutions of these problems.

SYSTEMS CONSIDERATIONS

Depending on the principal form of information processing in a computer, we may classify this machine into one of three groups; analog, hybrid, and digital. This classification scheme was originally applied to electronic computers, but is is clearly valid for optical machines as well. Most of what is called optical processing techniques belongs to the analog class; the best-known examples being spatial filtering, edge-sharpening, auto- and cross-correlation techniques based on the Fourier transformation properties of some optical elements. We might extend this definition and say that a film camera is a simple analog optical data processor and recorder. On the other end of the spectrum, an optical card or punched-tape reader is a digital optical processor.

A closely related idea is the consideration of how much data is processed simultaneously by the computer. Many analog processing techniques also are parallel processors; in the above-mentioned spatial filtering method all information is processed simultaneously in parallel. In fact, this seems to be the point where present-day computers need improvement most. Having achieved extremely high speed in processing individual bits, their through-puts (the number of bits processed per second) are mainly limited by the fact that relatively few bits are processed in parallel. It appears that there is a great present-day need for a computer system that could process great quantities of analog input information in parallel and present a simple, perhaps digital output in short time. (An existing example of such a system is the eye-brain combination).

There are basically three types of computer organization structures:

1. A Process Simulator is a machine whose structure simulates the sequence of cause and effect involved in a physical process. Differential analyzers, both digital and analog, belong to this class.

2. A Pattern Transformer is a machine capable of storing and modifying a complete pattern, this pattern being considered as a map describing a common property of a set of elements.

3. A Symbol Calculator is a machine that performs operations on a set of symbols. An example of this class is the conventional stored-program digital computer.

In view of these considerations, we investigated the following three main areas of optical data processing systems:

1. The parallel and mostly analog optical processing techniques, which utilize the holographic storage method.

2. High capacity, high throughput optical back-up memories to be connected directly to an existing, conventional electronic data processor.

3. Special computing systems, digital and to a high degree parallel, utilizing special-purpose electronic, parallel processors.

Optical Data Processing Techniques

Many of the most important signal processing steps, such as integration, differentiation, correlation, filtering, etc., can be performed with relative ease by providing suitable filters in the Fourier plane. One particularly interesting application of this theory concerns the recognition of a particular detail of an image. A so-called matched filter is placed at the Fourier hologram transform plane of the image, which transmits only the spatial frequency components corresponding to the transform of the detail to be recognized; the inverse Fourier transform of the filtered wavefront will provide bright spots at the center of the recognized detail. It should be noted that Fourier-transform-plane processing is not a new idea. There are, however, some new approaches that make this method more applicable to computer systems. One could put various "mask" filters in this plane and obtain the effects described above. It appears to us, however, that similar processing can be done by using a Fourier hologram record of the signal and to carry out the particular processing by a modulated coherent readout beam.

This "modulation" may simply be the selection of one of the higher fundamental transverse modes of a laser. Differentation, integration and edge sharpening can be accomplished by simple low order modes of a cavity. It also appears feasible to preprocess the signal and record only the result of the processing, by using a modulated reference beam at the recording of the hologram.

The technique described above is well adapted to a special purpose, relatively slow processor. It does not; however, have the ease of recording and access that is required from a subsystem of a conventional computer. At present, it is very difficult (although not impossible, and it has been done) to record an artificial hologram point-by-point, and the transparency type of recording of computer information is also a relatively slow process. Thus, it does not appear reasonable to expect that this type of Fourier plane processing will be an integral part of a general purpose computer in the near future.

Another application of holography can result in beam selectors, read-only memories, and associative memories. In most hologram recording experiments, one of the beams, the information beam, is modulated by the signal to be recorded, and the other beam, the reference beam, is an un-modulated (uniform amplitude, spherical wavefront) light beam. Readout of the hologram can be effected, theoretically, with either of these beams; the presence of the reference beam will result in an output beam similar to that of the original information beam. This works in reverse also; if the hologram is illuminated by the information beam, the original reference beam will be recreated at the output.

One can therefore see how a beam selector would work. If an appropriate address pattern is used as an information beam to store a hologram corresponding to a reference beam having a particular direction, then subsequent illumination of the hologram with that address pattern will recreate the original reference beam in the direction corresponding to the address. Super-position of such holograms, each consisting of a unique address-direction pair, will provide a library from which a beam direction may be selected by introducing the correct address.

The use of volume holography, in which distinct records are distinguished from each other by means of the direction of illumination, to provide a memory hologram together with a beam selector hologram for acquisition could be combined to form a read-only memory. Since, presumably, more than one address of the beam selector might be activated at once, therefore calling out a selected multiplicity of memory records simultaneously, a considerable degree of free-association may be achieved with such a system.

Choice of addesss pattern is arbitrary, and one may therefore generalize the idea by saying that any coherent input beam or input pattern can be transformed into a different, arbitrary output beam or output pattern. If a means for selective modification of the memory hologram could be provided, this scheme would be a general optical memory. This memory would also satisfy the requirements of an associative memory, since any input pattern can be associated with a certain output pattern and combination of input patterns (e.g., a pattern of input patterns) will produce a superposition or association of output patterns. The input patterns are entirely general, and in principle can be digital arrays or other arbitrary patterns.

The problem of realizing such a memory is not a theroretical one. There are many practical problems, mainly concerning noise, low light efficiency and exceptionally high mechanical stability requirements.

High Capacity Optical Memories

The principal aim of this study is to search for ways to convert the potentially high capacity of the optical storage elements into high throughput of the whole storage system. Some advanced electronic memories retrieve individual bits in the order of 10 nanoseconds, and it is not probable that optical memories will exceed this speed for performing individual operations by a substantial factor. Thus, the only other way that remains open for improvement of memory throughput is to process more bits simultaneously; i.e., to increase the number of parallel operations. The transfer of large amounts of information in a parallel way is no problem for optical processors; lenses are capable of imaging well over 10^6 resolvable elements simultaneously. The throughput of the purely optical components is typically very high.

If a large amount of redundant, raw data is recorded in an optical storage medium and then transferred in parallel in large blocks into a high speed data reducer or pattern recognizer or some such device, the system is well optimized for high throughput.

Presently available optical storage technology can provide fast parallel read-in or slow serial read-in, fast parallel read-out or slow serial read-out, very high capacity (10^{10} bits) memories; these are presently suitable mainly for mass data storage and read-only applications. All three types of computers mentioned need this type of back-up memory. In the case of the Process Simulator, this memory might contain the forcing function, sets of parameters, previous solutions, previously computed partial solutions either in sampled or in analog recorded form. Slow (serial) writing speeds and limited erasability might not be a handicap in such machines. For the Symbol Processor type of computer, such a back-up memory can be used to store subroutines, tables of often-used functions, or to provide a semi-permanent filing system of relevant data. Pattern Transformer types of computers and large capacity optical memories are well adapted to each other.

Digital information can be recorded in an optical storage medium in two basically different ways:

a. Direct, binary recording of spots on a film of the storage material.

b. Hologram recording, either on a thin film which yields a surface (two-dimensional) hologram or throughout a relatively thick block of material which yields a three-dimensional volume (Bragg-Angle) hologram.

The recording and read-out of binary spots present difficulties with registration and addressing, but otherwise the procedure is straightforward. Hologram recording requires highly coherent light, high degrees of mechanical stability during storage, and coherent illumination for read-out. The thickness of the recording medium does not affect the resolution of the holographic storage, but it severely limits the smallest resolvable spot size in the spot-recording method. Read-out signal-to-noise ratios depend strongly on the storage material used.

If an erasable material is used, individual spots can be erased with relative ease, whereas it is much more difficult if not impossible to selectively erase a hologram. Total erasure of the memory is, of course, possible in both cases.

Since the volume, or Bragg-Angle hologram utilizes the volume of the recording material, it appears that more information can be stored in this way in a unit volume than in either the spot-recording, or surface hologram approach. The increased noise due to the many superimposed holograms might, however, prevent realization of the full capacity of the volume hologram memory. Noise build-up in the material will eventually determine how many holograms one can superimpose and record in a single volume. Best utilization of a volume recording material can be achieved if a mosaic of small hologram blocks is recorded independently, with the maximum number of holograms recorded in any one block being determined by the inherent noise level. Each of these small holograms would contain many bits of information and the hologram would be made from a spot-recorded transparency of the same information.

Another point of comparison between spot-recordings and holograms is the read-out light efficiency. This efficiency is close to 100% for spot recordings, whereas it is only about a maximum 6% for surface absorption holograms and even less for volume holograms.

For target memory capacity of 10^{10} resolvable bits, spot-recording (which must be done on a single thin-film surface) requires on the order of 10^5 randomly-and rapidly-accessible positions in each of the two dimensions. Present-day beam deflection and positioning technology is not sufficient to accomplish this requirement on an individual bit approach. Thus, a compromise would have to be reached for spot-recording between random access, speed, and memory capacity. It is most likely that in the applications mentioned above, data will be organized into a number of large blocks (or frames), each of which will be randomly accessible by mechanical means, and a sequential scanner will be used to read the contents of each large block of perhaps $10^3 \times 10^3$ bits each. If data were organized into smaller blocks, such as 25 x 25 bits, perhaps electro-optic (fast) random access can be provided within this small block. This approach would, however, lengthen the access time of the blocks themselves, since the number of blocks would increase tremendously if the total capacity is to remain constant.

The read-in problems of hologram recording are more complex. A method will be needed to form a coherent image of a block of data at a specific plane so that, from this image, a volume hologram could be recorded in the desired sector of the recording medium under proper angular conditions. The angles of both the information-carrying and the reference beams would need to be controlled as well as the location of the sector in which the hologram is recorded. These problems do not involve difficulties in principle, but only those of a technological nature. The coherent input information beam might be created in two different ways:

1. A laser beam serially stores the frame, dot-by-dot, on a photosensitive film of some material. This film is then used as a mask to create the information beam needed for hologram recording. The material of the film must be such, that it is not affected by the hologram-froming light.

2. An electro-optic plate could be used as the mask for the hologram-forming light beam. Such a plate would be a mosaic of electro-optic cells (or fibers) with individual selection electrodes and a common ground. The mosaic would match the pattern of the block of information. Application of voltages to selected cells would result in phase modulation of the wavefront transmitted to the hologram storage. This method has the advantages of being a faster, one-step method, and involves only a parallel channel between the computer electronics and the storage medium.

These considerations indicate that the spot-recording is presently the closest to practical applications. The hologram storage methods need more investigation, particularly on the effect of superposition of many holograms on the output signal from a single hologram read-out. Signal-to-noise ratios, the degree of mechanical tolerance and stability requirements, and other material problems are also significant subjects for investigation. It should be emphasized though, that in certain applications the hologram is more than just a representation of the stored information, it is already in a readily usable form.

A 10^{10} bit spot storage system using a 1 micron thick storage film of some material, a 1 micron spot diameter, and blocks of $10^4 \times 10^4$ resolvable elements, would need 100 of these 1 cm x 1 cm blocks available in a slow, random-accessing system. Similar capacity is present in a much smaller volume, if volume holography is used, but here we need experimental numbers of the kind mentioned above to determine the exact size of material needed.

Special Computer Systems

Conventional computers have a throughput of 10^9 bits/second for simple logic operations; for more complicated operations such as multiplication this figure is much lower. Optical memories could have throughputs on the order of 10^{10} bits/second, and thus, they would not be matched well to conventional systems. An appreciable increase in computer speed or extensive parallel organization would be required to make full use of the large throughputs possible with optical memories.

It seems feasible to construct an electronic parallel processor which would operate on all of the digits of a few input blocks simultaneously. The individual logic elements would be integrated circuits, with one connection for each input and output bit. Many operations could be performed on the blocks, which would be interpreted as digitized images or as point-by-point descriptions of two-dimensional functions. In the latter case, for instance, each sampling point of the function could be specified by a set of 9 binary dots; i.e., with better than

0.2% resolution. If a block would contain $10^3 \times 10^3$ sample points, then with the above quantization, 9×10^6 spots are required, and the electronic processor is obliged to have the same number of elements.

Such a computer could be organized to have a large-capacity, high-throughput optical memory with its corresponding buffer memory, a central control, which would interpret a block as a program and a set of special-purpose parallel processors, one for each distinct instruction. All block transfers would be done through the buffer memory. Each processor would have its own local input and output block registers.

Operations to be performed are such as addition, multiplication, inversion, division, function transformation integration with any one of the space variables, logical operations on corresponding bits, interactions between each bit and its neighbors, shifts, scaling, changes of independent variables, obtaining parameters defining geometrical, topological or algebraic properties of the blocks, etc.

Such a machine would be applicable mainly in the fields of pattern recognition and processing, complex control and decision problems, adaptive learning, and in approximate treatment of algebraic problems dealing with two-dimensional functions. The realization of such a machine on a small scale (e.g., 10^6 bits) is feasible, but the success of large scale realization will require further advances in integrated circuit technology.

BRAGG-ANGLE DISCRIMINATION

A theory of Bragg-Angle discrimination was developed for application to the selective retrieval of multiple images from a crystal containing the holograms of those images. The infon concept gives a very visual method for the description and an intuitive, and in some cases rigorous, derivation of the information storage capability of a crystal. The three degrees of freedom in infon k-space can in some configuration correspond to the two-dimensions of the information transparency with the Bragg-Angle discrimination providing the third coordinate.

For the discussion of the discrimination experiments however, the formulas developed by E. N. Leith et al, serve as the basis. Two additions are contained in the present work. The two additions are concerned with corrections for the existence of fringe attenuation caused by absorption of light within the recording medium, and with corrections for the shift of Bragg-Angle with the angle of illumination as a result of effects due to crystal index of refraction.

The read-out intensity as a function of crystal angle depends on the color density, the crystal thickness, the index of refraction, the information and reference angles and the wavelength of the laser light. Complicated formulas were obtained for a complete explanation of the Bragg attenuation. A somewhat simplified approach is described below.

We can group the parameters in two variables. Let A express the angle of crystal rotation from the storage position in relative units. Let the size of this unit express the dependence on the geometrical parameters, including crystal thickness, and the index of refraction. Let D. be the density parameter of the crystal at this wavelength. In terms of these parameters the read-out intensity has the form:

$$I = \text{const.} \frac{\cosh D - \cos A}{D^2 + A^2}$$

Zero color density leads to the form $(1-\cos A)/A^2 = 2\sin^2(A/2)/A^2$. Thus, a light crystal will have a Bragg attenuation curve with periodic minima and sidelobes. A very dark crystal won't show such periodicity, the curve is approximately of the form $\cosh D/(D^2+A^2)$. The angular dependence parameter A is approximately

$$A = 2 \frac{\theta}{\theta\ \text{Bragg}} \quad \text{where } \theta_B = \frac{n}{n-1} \quad \frac{\lambda}{2L\sin /2}$$

Experiments were carried out which confirmed the theory of Bragg-Angle discrimination, as extended in detail. One feature which is particularly clarified by the extended theory, as well as by the supporting experiments, is that the effective thickness of the crystal, which is the cominant factor influencing angular resolution of images, is controlled in an absorbing medium by the attenuation of fringe contrast resulting from absorption, rather than by the nominal exterior dimensions of the material. A consequence of this result is that high Bragg-Angle resolution, with very close angular separation between images, is favored by the use of crystals with low color density and large physical dimensions for the achievement of a specific total optical thickness, rather than by physically thin, high-color-density material.

Precise Bragg resolution measurements were made at different reference angles. The attenuation curves showed the existence of side lobes around the central maximum. The minima between these lobes and the central maximum formed an arithmetic progression. The small angular interval of this progression is defined as the Bragg-Angle, θ_B. At higher color densities the first minima shift away from the center; at high enough densities the first minima disappear and the curve shows less and less periodicity.

The crystal angle was measured with the aid of an optical monitor. A mirror was mounted on top of the crystal and the rotation of this mirror deflected a laser beam. The four-meter deflection arm of this beam assured us an angle sensitivity of 1/8000 radians per mm deflection.

For a point source, the following are representative results:

Ref.Angle	10^o	30^o	50^o	70^o
θ_B(min. of arc)	9.1	2.9	1.7	1.3

The crystal was 2 mm thick and its normal vector pointed to the angular bisector of the information and reference beams.

The results for extended objects are more complicated, but are consistent with the simple point source problem. Here, the Bragg-Angle does not have such a clear definition because contributions to the holographic reconstruction from different areas of the hologram may have different Bragg-Angles. The largest of these Bragg-Angles may be taken as the attenuation angle of the compound image.

Normalized brightness curves (Figure 2,) show the dual influence of thickness and color density. The thickness defines the periodicity while this is masked by the exponential attenuation of the higher optical densities.

Very low color density corresponds to the case of non-exponential storage media, such as photographic emulsions. With the introduction of color, the minima become greater than zero and the ripple is reduced. A very dark crystal shows no minima and only a very slight ripple in the curve. The angle of discrimination increases. The effective thickness of the crystal is reduced. For light crystals the physical thickness is important; for dense crystals the optical penetration depth is the dominant factor.

Discrimination criteria for neighboring stored images have to be defined in terms of the acceptable signal to noise ratio. Figure 5. shows the rotation angle required for the attenuation of the holographic image below some chosen threshold. Choice of attenuation level will depend upon the application; 5:1 may suffice if only two detectable levels are required in the read-out (e.g., alphanumerics, line drawings), but a greater ratio will be needed for continuous tone pictures.

The angle is given in units of Θ_B. This Θ_{Bragg} was defined as the angle between the peak and the first null for a light crystal. The discontinuity is caused by the sidelobes of intensity; at a certain color density they break through the attenuation ratio specified and increase the required rotation angle suddenly.

Experiments were also conducted to verify the inapplicability of a second orthogonal rotation angle to yield additional independent Bragg selection. It was experimentally demonstrated that only a single rotation angle provides unique Bragg selection, and that rotation in a direction perpendicular to the first direction of rotation does not yield selectivity which is independent of the first. Thus, the total capacity of a crystal for storage of holograms which are to be discriminated by Bragg selection is obtained by dividing the total angular swing by the selection interval. Due to physical and mechanical considerations, the total available swing of the crystal would normally be from 30° to 45°; in the crystals employed for these experiments, the Bragg discrimination interval is approximately 0.1°. Thus, at least 300 to 500 holograms may be discriminated. With expected reductions in the discrimination interval, a total capacity of well over 1000 holograms is expected to be discriminable; of course, each hologram may also contain more than a single image (thus increasing the total proportionately), which may be separated by other techniques.

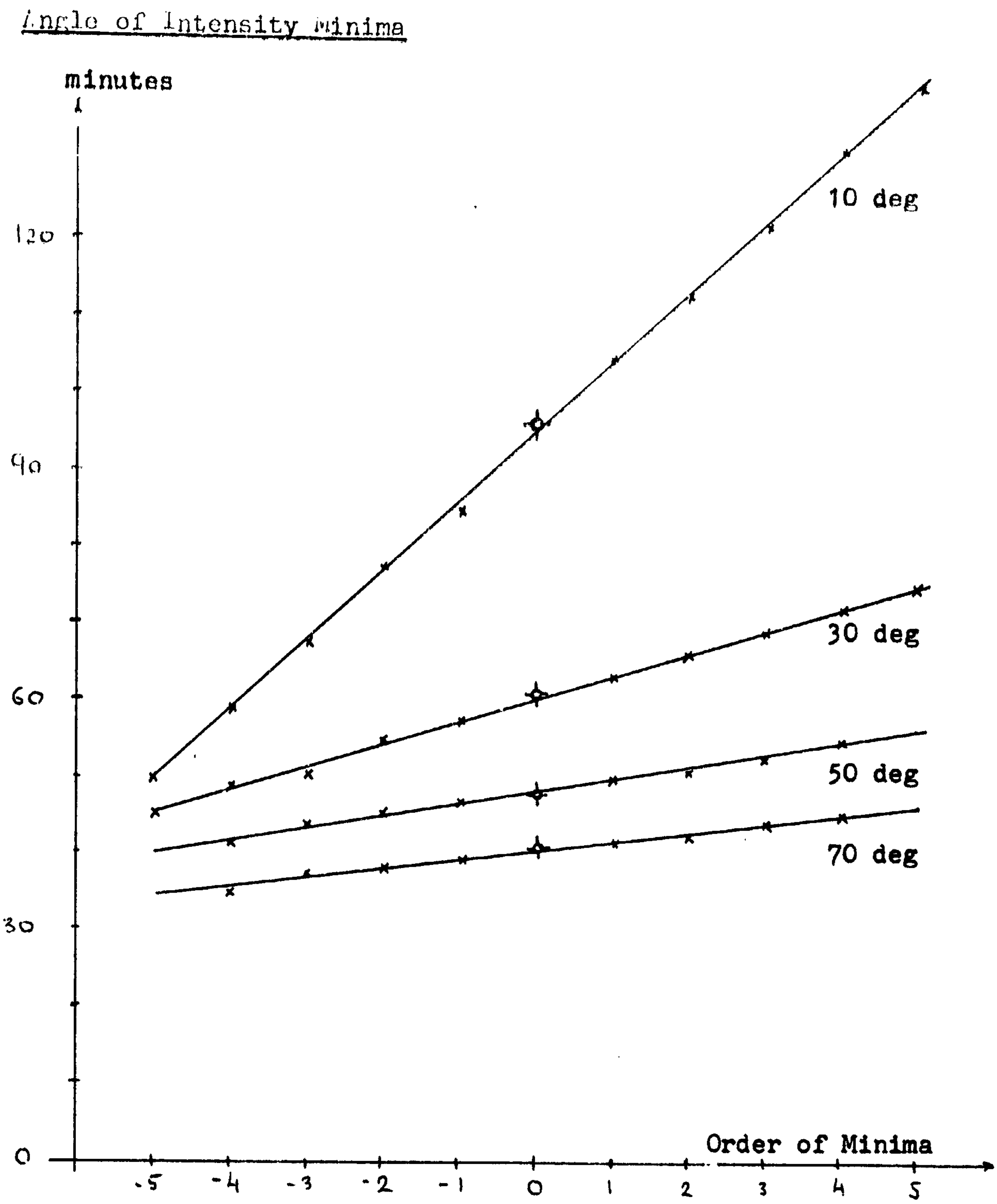


Figure 1. Rotation angle vs. the order of the minima. The zeroth order is the central maximum.

Read-out Brightness

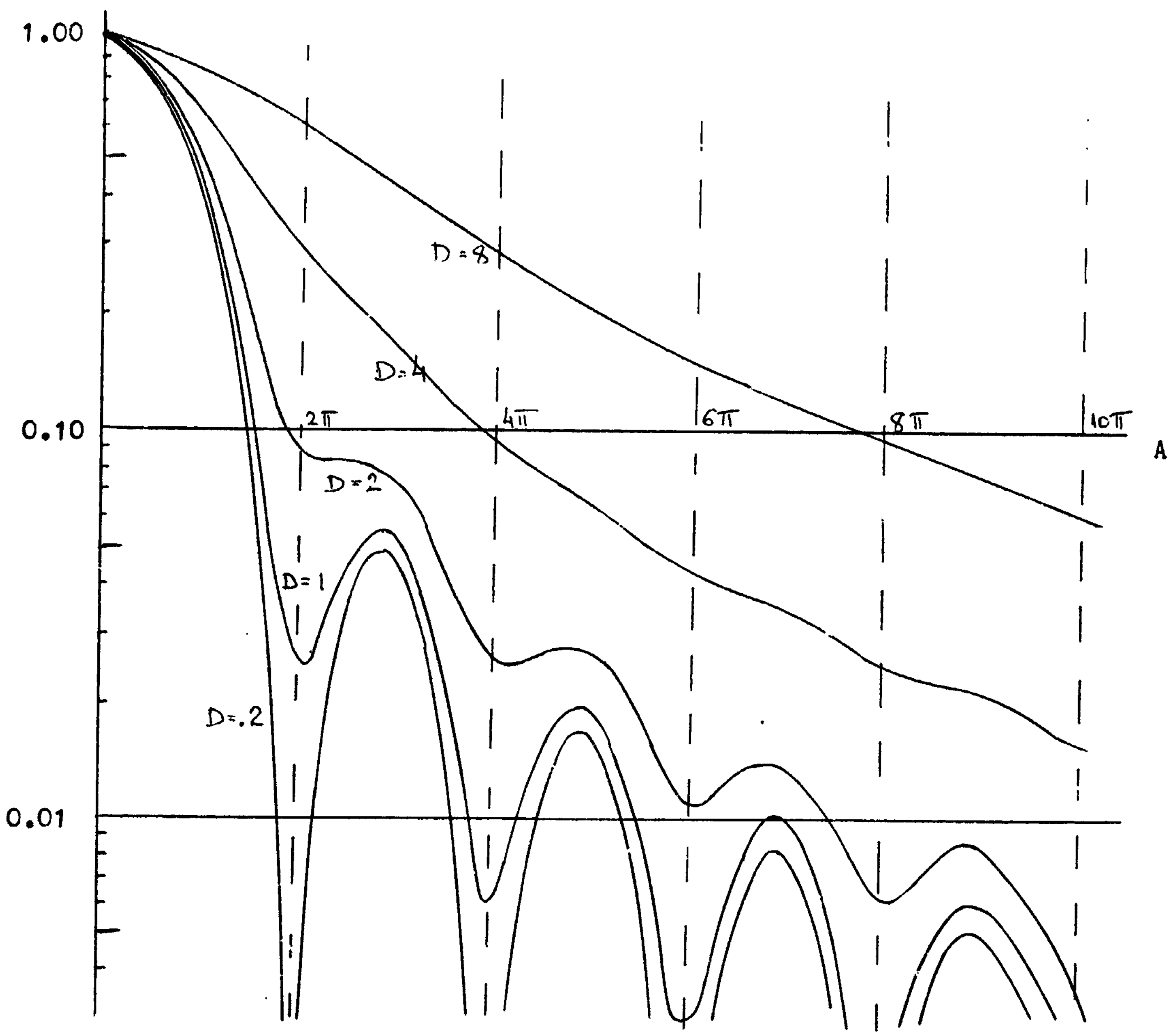


Figure 2. Holographic read-out brightness vs. crystal angle parameter for various optical densities.

Read-out Intensity

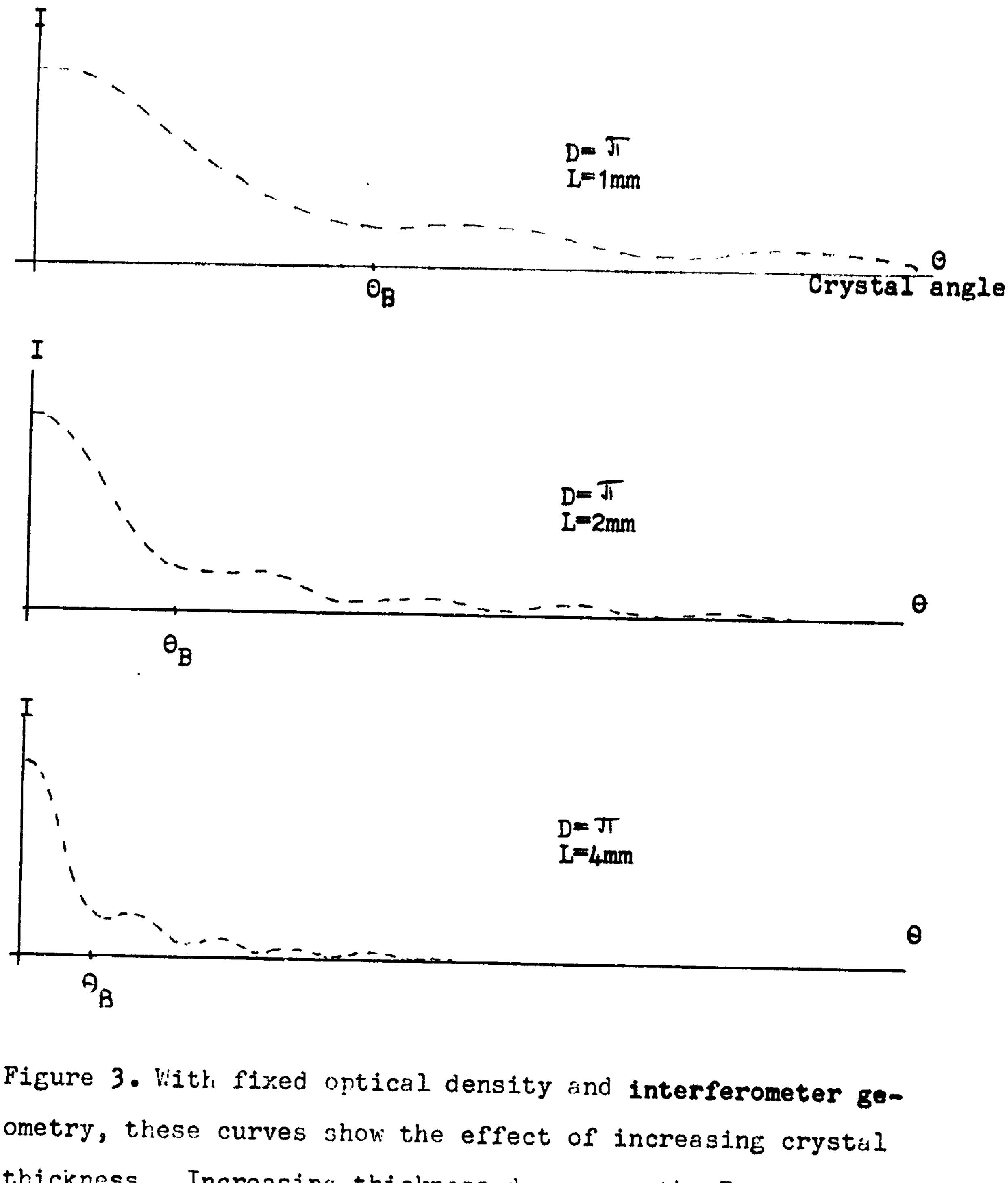


Figure 3. With fixed optical density and **interferometer geometry**, these curves show the effect of increasing crystal thickness. Increasing thickness decreases the Bragg-Angle, thus allowing the storage of more pictures.

Read-out Intensity

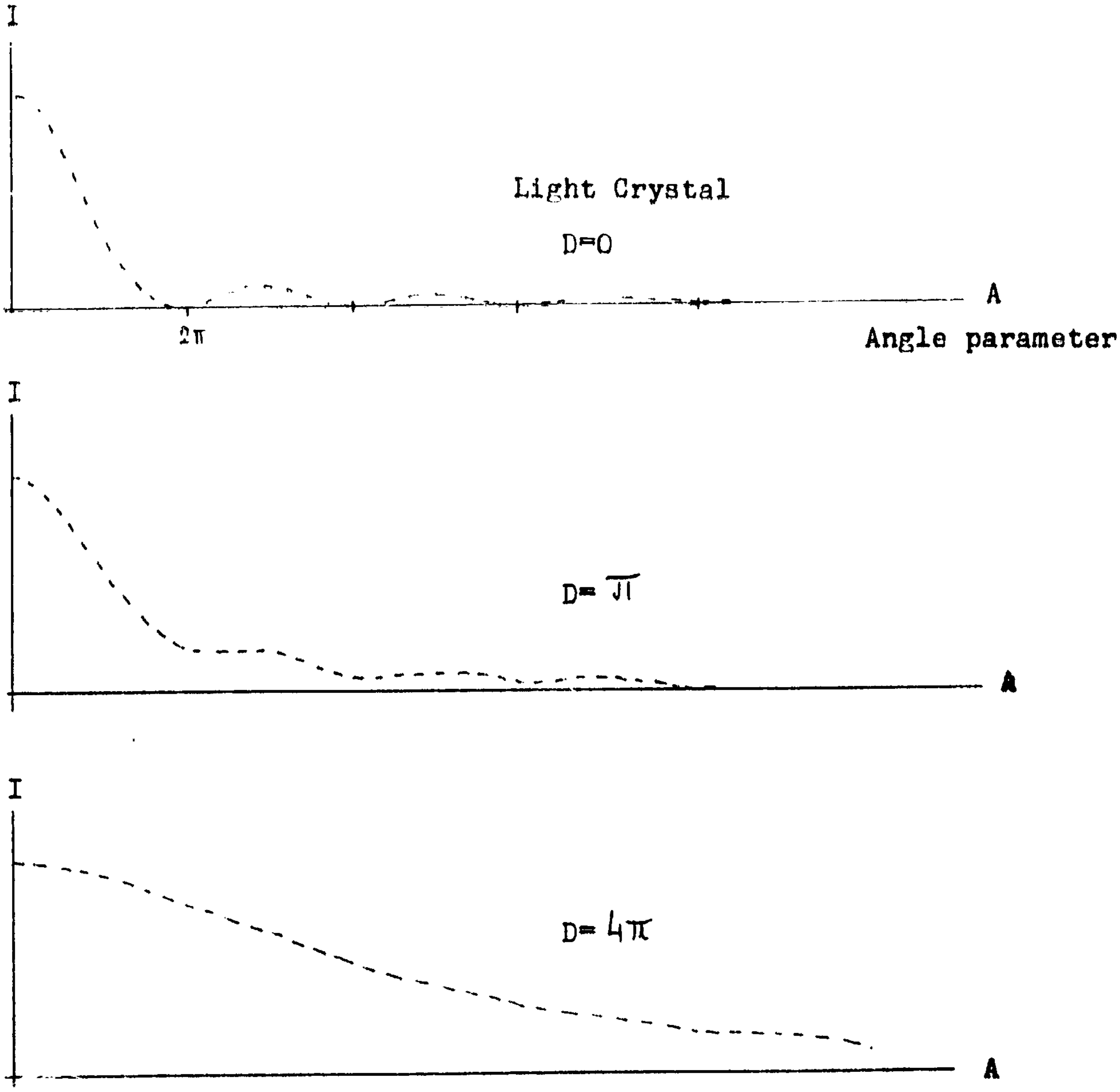


Figure 4. With fixed crystal thickness and interferometer geometry, the three curves show the effect of increasing color density.

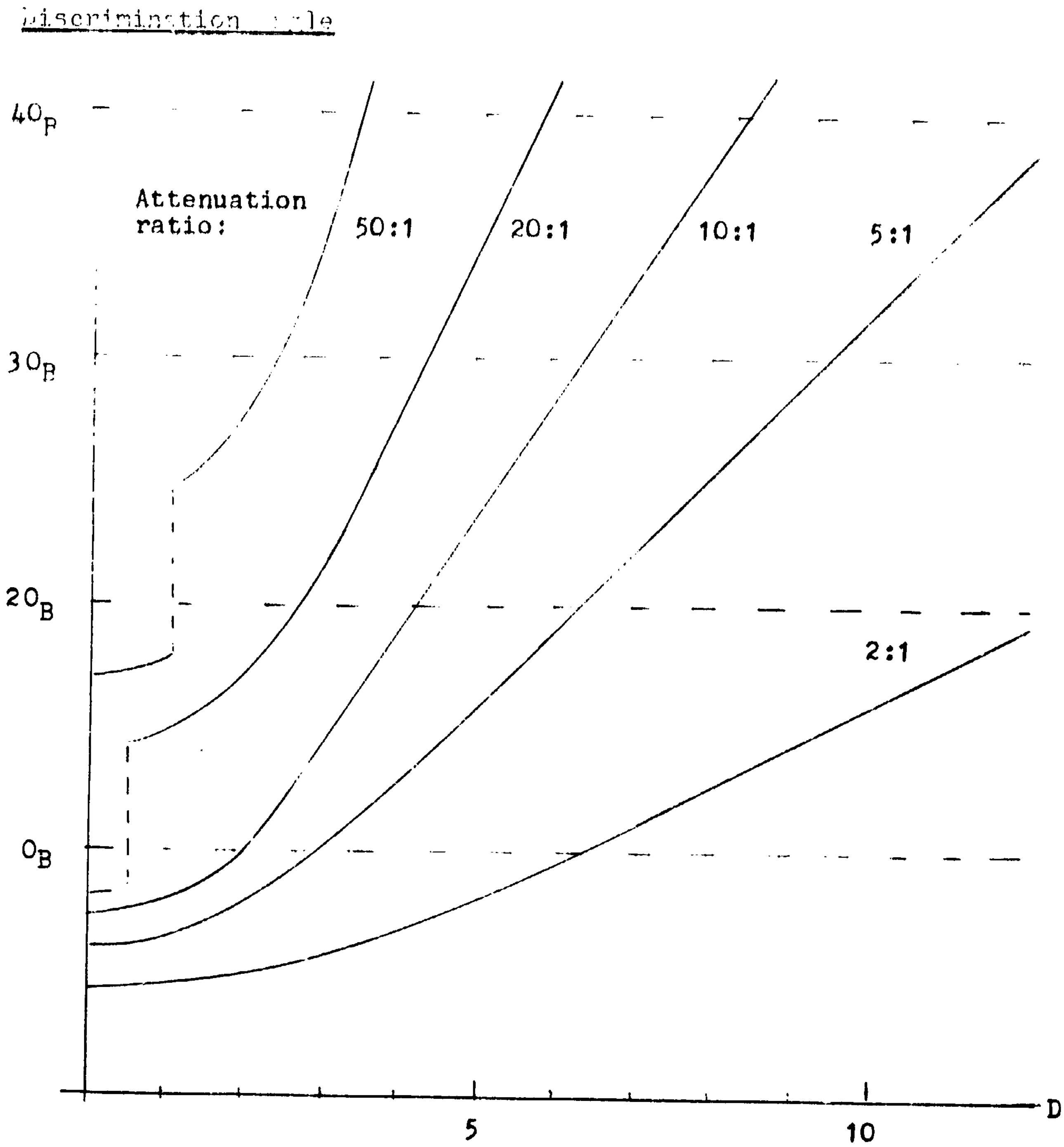


Figure 5. Discrimination angle vs. color density parameter D for a set of attenuation ratios.

RESOLUTION

In any real optical system the idealized concept of resolution must be supplemented with considerations of the noise introduced by the active, passive and storage elements. Resolution may be given in terms of line pairs or in terms of spatial frequency response curves. The image may be recorded holographically or spot-by-spot. In a general interpretation of resolution, detectability must be included; thus, signal-to-noise limitations and crosstalk (false readout) problems should be considered.

When we consider possible computer applications, we must distinguish two types of resolution criteria. In a hard-bit memory, the read-out detectability must be good enough to recover all the stored bits. The loss of even one bit may upset the whole program. In a soft-bit memory, we only require a certain percentage of the bits to be recoverable. Present electronic computers work mostly with hard-bit memories; the human brain operates on a soft-bit storage system. Another example of a soft-bit memory is photography. The loss of a fraction of one percent of the information on a moon photo will not detract from the success of the mission.

Our present work centers on holographic storage. We have explored both the hard-bit and the soft-bit capabilities of the KBr-H crystal.

Soft-bit resolution experiments were completed of holographic recordings in a colored crystal using a standard bar-test pattern. The number of lines/mm resolved, N, depends on the crystal aperture and the distance between the test pattern and the crystal. The limit due to diffraction alone is $N = 1300\ D/L$ at 6328 Å, and the results of our measurement followed this theoretical, diffraction-limited relation (where D is the available crystal aperture and L is the separation distance between crystal and test pattern) up to an aperture of 7 mm diameter. In a typical measurement, N = 91 lines/mm, D = 7 mm, L = 100 mm. The theoretically-expected resolution pattern of an aperture with this type of illumination, i.e., another Gaussian pattern, was observed experimentally. Experimental results indicated that diffraction-limited performance was obtained at a wide range of source distances for an effective aperture of approximately 7 mm. This aperture corresponds to a dimension approximately 1/3 of the maximum crystal dimension, and was confirmed by visual inspection to be the portion of crystal surface with acceptable $\lambda/4$ polish. Since the KBr crystals employed are very soft, and also hygroscopic, the attainment of adequate polish (since accomplished) was a continuing limitation throughout the investigations.

Liquid "gating" was explored as a method of increasing resolution by compensating for imperfect polish with the aid of a liquid surface. Suitable index-matching liquids were found and resolution experiments showed great improvement, but some practical problems arose that make the use of this method cumbersome at this time. The liquids tend to dissolve part of the crystal, and (especially under heat-cycling conditions) re-deposit it on the window. An even greater problem was our inability to find a liquid that, in addition to its other requirements, will transmit ultraviolet light.

A hard-bit binary test has been constructed. Instead of line-pairs, this consists of a two dimensional lattice of binary bits. The bit of each lattice is transparent or opaque with 0.5 probability. The randomness of these bits was assured by the use of a table of random numbers. Illustration 9 shows the direct read-through; Illustration 10 shows a holographic readout of the same pattern. Illustrations 11-13 show the effect of progressively limited aperture on the resolution.

An additional problem affecting resolution in multiple-hologram records of digital computer data, for example, is the possibility of higher-order interference, or crosstalk, originating from the highly periodic arrays of stored data. This question was investigated both theoretically and experimentally, with results favorable to the circumstances of present crystal utilization practice.

Two points located in the image plane at $\bar{a}$ and $\bar{b}$ with respect to the reference beam, yield a pattern of secondary images with varying intensity. The order of the false images corresponds to the order of nonlinearity in the storage medium. At a location $(n\bar{a} + m\bar{b})$, the order $O(n,m)$ is

$$O(n,m) = |n| + |m| \qquad (n,m \text{ integer})$$

Increasing order means decreasing intensity.

In a typical configuration the separation between two information bits is small compared to their angular separation from the reference beam. Thus only the odd order would be within the image area.

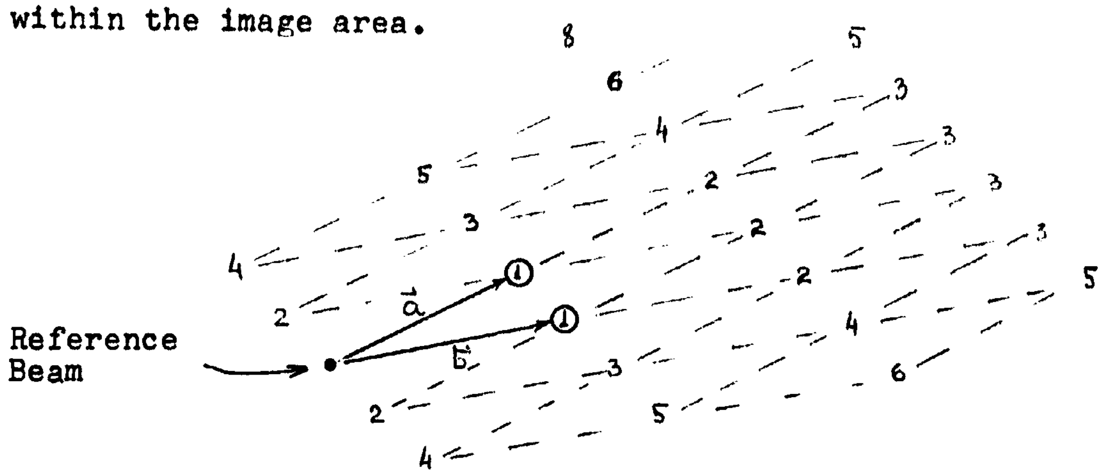


FIGURE 6. Orders of Crosstalk
Between Two Point-Images in a Hologram

In some cases not pertinent to hologram storage in crystals there is a possibility of serious difficulties with such interference, arising from superposition of odd-order contributions (even-order contributions do not appear at the image plane) when strong non-linearities in recording sensitivity of the medium are characteristic. These circumstances do not arise in crystal hologram recording, and the difficulty has been shown, both theoretically and experimentally, to be of no significance.

A resolution-preserving technique of crucial importance for multiple-image hologram recording in thick crystals was demonstrated and perfected. This technique simply consists of reversing the direction of reference-beam illumination for image read-out, or, the equivalent, to flip the crystal by 180° for read-out. In effect, this process converts the reconstructed virtual image into a real image. In thick storage media this requires a plane wave reference beam and a well-polished plane parallel crystal. The significance of this method is that it eliminates the imaging lens limitations on resolution and flatness of field. A 10,000 X 10,000 bit image field is quite conceivable without imaging optics. Present size and polish limitations only allow us to recover a 1,000 X 1,000 bit field.

Investigations were also performed experimentally to ascertain the optimum optical design, especially of aperture-stop locations, to provide maximum resolution and freedom from spurious noise. These results are also relevant to general hologram recording in photographic media as well as crystals.

In the stationary crystal and reference beam read-out system one should preferably provide a real exit pupil by illuminating

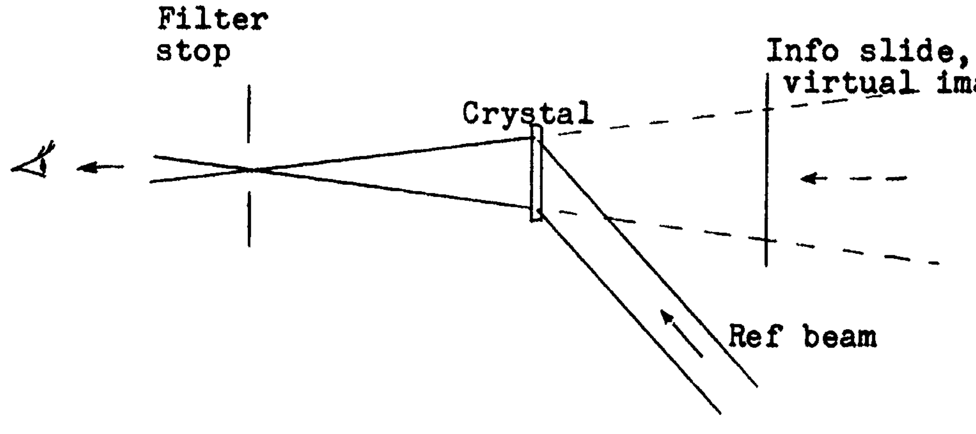


FIGURE 7. Noise Filtering for Stationary Crystal

the slide with a convergent beam that comes to a focus past the crystal. At this location a variable aperture stop will provide optimal filtering. There is a trade-off between the noise and the signal that passes through the stop. One should close this stop to allow just the necessary resolution to pass through.

In the 180° flip system, the exit pupil during storage should be virtual, located between the slide and the crystal. During read-out the crystal is turned around and it carries the exit pupil over on to the other side. As above, a stop should be located at this position.

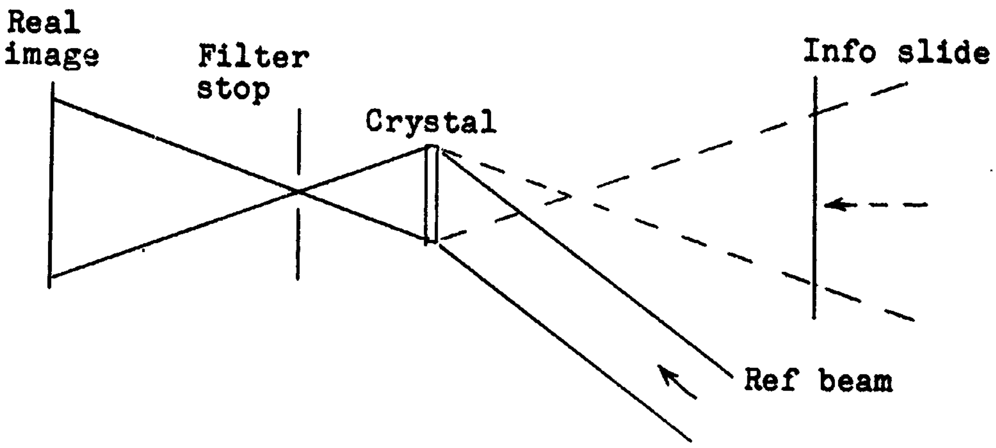


FIGURE 8. Noise Filtering for the 180°-Flip Crystal

Illustrations one and two show a well filtered high resolution (5-6), high contrast read-through and read-out respectively. Ill. 3 is a typically bad hot storage - cold read-out hologram

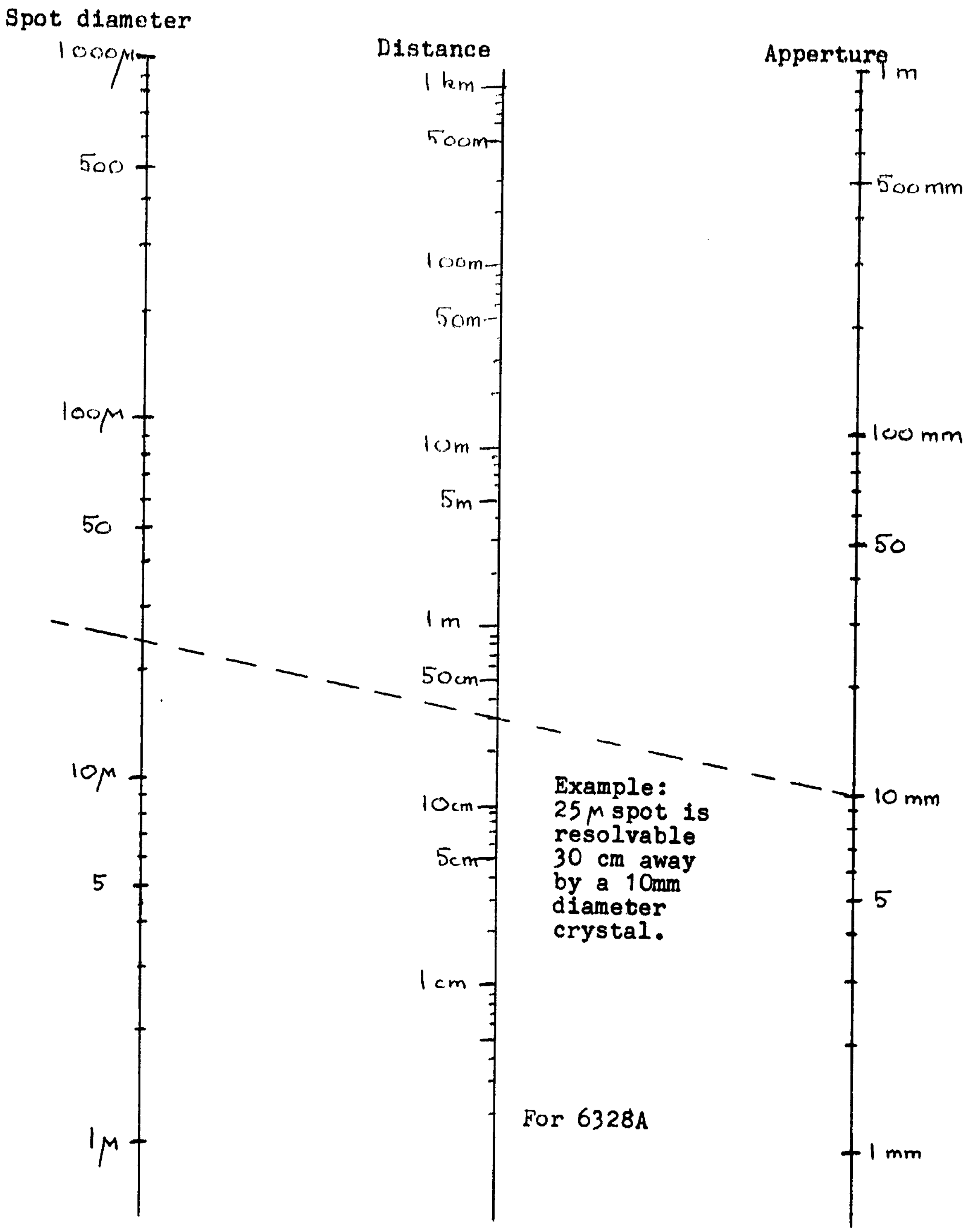


FIGURE 9. Resolution - Distance - Aperture Nomogram

ERASURE

The reversibility of some color-center transitions offers one possible method for an optical memory with write and erase capabilities. An example of this type of memory is the cryogenic KBr, $F - F^1$ system, using the conventional spot-by-spot recording technique. The He-Ne laser red line provides the writing beam ($F - F'$ transition) and the He-Ne 1150 nm infrared line is the erasing beam. ($F^1 - F$). Erasure can be done spot-by-spot, word-by-word, by blocks or the whole memory can be erased simultaneously. Such a memory has been successfully tested by Carson Laboratories.

The KBr;H, F - U storage system uses red as the writing beam; erasure is accomplished through recoloration by a UV lamp. In the spot-by-spot storage configuration this system has the disadvantage over the $F - F^1$ transition that, at present, no UV laser is available. Thus, only larger areas of the crystal can be erased, the selectivity is quite limited.

In the multiple image holographic information storage method, a new kind of selective erasure becomes possible. This erasure does not depend on the reversibility of the color-center transitions. This selective erasure does not recolor, but destroys the fringes by an additional exposure of the same information with a half wave retardation introduced into the reference beam. This phase-shift changes the interference fringes so that the formerly dark areas are now bright and vice versa. The sum of these two exposures cancels the holographic information corresponding to this image.

A simple mathematical model is satisfactory for the illustration of the principle of selective erasing. Let A represent the complex light amplitude of the information beam and B represent that of the reference beam. Storage in the recording medium is proportional to the intensity of the combined beams.

$$\text{STORAGE:} \quad |A+B|^2 = AA^* + BB^* + AB^* + A^*B$$

The first two terms are slowly varying functions of position and depend on the intensities of the two beams. These dc terms contain no holographic information. The third term gives the first order holographic readout while the last term yields the minus first order. These ac terms are rapidly varying functions; they contain both phase and intensity information.

The half-wave retardation of the reference beam means multiplication by $\exp(i\pi) = -1$. Thus we have

$$\text{ERASURE:} \quad |A-B|^2 = AA^* + BB^* - AB^* - A^*B$$

If the original storage is unchanged, the erasure will be complete.

STORAGE + ERASURE: $2(AA^* + BB^*)$ = dc terms only. The holographic information has been erased, and the resultant effect is the equivalent of two exposures in terms of dc bleaching levels, but contains no ac.

Two phase shifters were built; an analog zero-to-six wavelength shifter using heat expansion, and a binary half-wave plate in the reference beam and an external polarization rotator.

The latter system, especially, has been found to be very successful. It has the advantage over the first phase shifter that it provides an exact phase shift and has no moving parts in the interferometer.

The selective erasure experiments were performed on an equal path variable angle interferometer. A $\lambda/2$ phase shift in the reference beam created a shift in the fringe system. This added erasure exposure cancels the information carrying AC component of the original storage exposure.

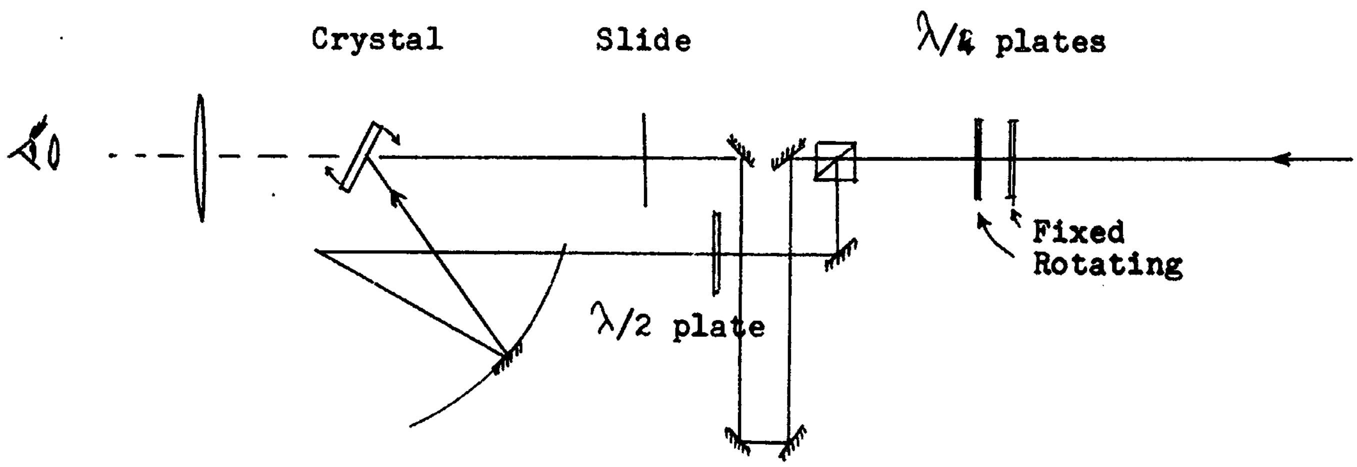


Figure 10. Equal path, variable angle interferometer with a $\lambda/2$ phase shifter in the reference beam.

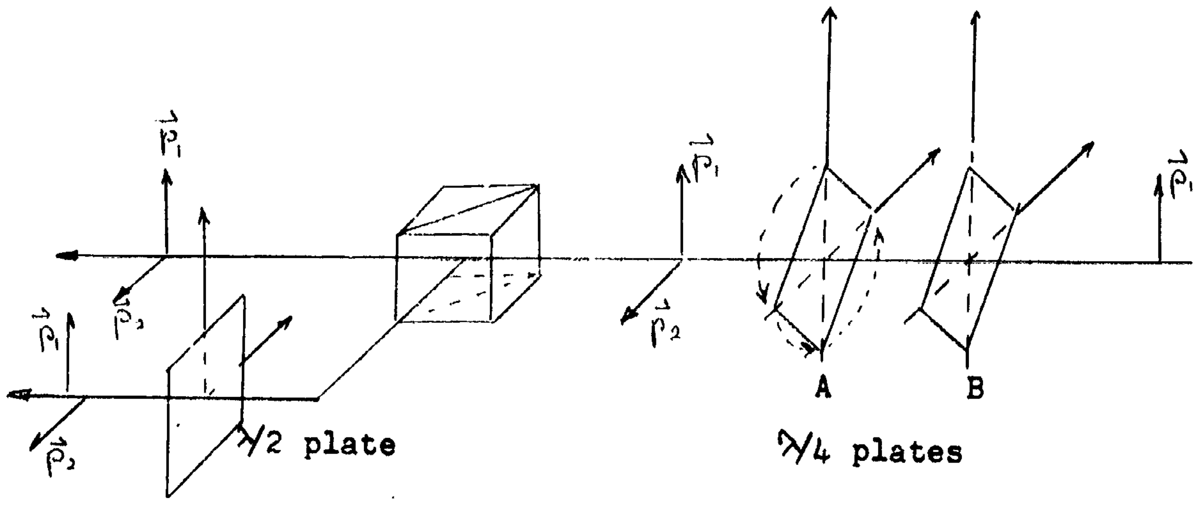


Figure 11. The $\lambda/2$ phase shifter. The fixed (B) and the rotating (A) circular polarizers are mounted on the laser and provide polarization p_1 for storage and p_2 for erasure. The $\lambda/2$ plate in the reference beam retards it by a half wave when the polarization is turned to p_2.

Visual observation of interference between the readout image of the stored holographic pattern and a reduced intensity image of the information carrying beam was employed successfully for monitoring the progress of erasing and for making fine alignment adjustments. The tolerances of alignment required for perfect erasure were found to be of the order of one-tenth wavelength, and adjustments of this precision required visual monitoring.

All erasure experiments yielded successful results over an increasingly difficult range of subjects, progressing from a point source pattern to a complex transparency. This method; however, has severe limitations. It requires the availability of the original information slide; the interferometer has to recreate the original storage conditions with great accuracy and the color-center distribution in the crystal has to be identical to the distribution it had during storage of the information.

Closed loop techniques can help solve the first two problems. An erasure slide could be created by reading out and storing the information in an intermediate storage medium, either as an image , or as a hologram. This intermediate storage could be used for erasure of this information. The visual monitoring technique used in the precision alignment of the erasure is another closed loop approach. The change in the color-center distribution is the factor that ultimately limits the usefulness of this method. In a multiple hologram system, there may be numerous storage and read-out exposures of different information slides between storage and erasure. The color density and the fringe contrast changes in such a way that the erasure exposure will not be able to erase throughout the volume of the crystal.

If the original storage has deteriorated unevenly in the crystal by a factor C(x,y,z), then the erasure cannot be complete.

$$C(\text{STORAGE + ERASURE}): (C+1)\ (AA^{*}+BB^{*}) + (C-1)\ (AB^{*}+A^{*}B)$$

The amount of uneven deterioration will determine the feasibility of selective erasure in a given application. Illustration 4 shows a set of very fine fringes superimposed over the image. This is a typical result of an erasure attempt when the illuminating bean is misaligned. Illustrations 5. and 6. show increasingly better alignment; with 6. showing two broad erasure bands only. Illustration 7. shows the combined effect of beam and slide misalignment. Picture 8. shows the residual traces of the erased information. The hologram intensity was 5% of its pre-erasure value. This five percent residue is most likely caused by imperfect phaseshift or a drop in the laser power between storage and erasure.

MULTIPLE HOLOGRAMS

Investigation of multiple-hologram storage conditions yielding the maximum number of retrievably recorded holograms in a crystal was not completed under this contract. Initial experiments succeeded in storing about 35 good-quality retrievable holograms, of which 12 were of nearly diffraction-limited quality. A number of techniques were conceived late in the program which showed promise of improving and extending these results, but there was insufficient time and money remaining to work out the details and the effects of the new concepts.

Three principal factors were considered in a limited way; namely, heat, bias, and exposure programming. The effects of heating the crystal during exposure (recording the hologram) with subsequent cooling to room temperature or less for non-destructive read-out, are dual in nature. First, the change of temperature of the crystal introduces a dimensional variation between writing and reading; since the interference surfaces are not perfectly plane, in general, there will be some image distortion introduced in addition to the modification of Bragg Angle selection. Second, the existence of heated air currents in the field of view during recording generates unwanted noise; this could be removed by the use of an evacuated interferometer in principle, but evacuation was not attempted.

The effect of bias buildup during multiple exposures is the most serious difficulty in principle. This effect is caused by the gradual depletion of dynamic range, or the available color-change capability of the crystal. If only a single hologram is stored, the entire range of optical density of the crystal may be utilized (e.g., optical density of 2 or more, or a contrast range of 100:1 or greater) to record the information. When two holograms are stored in the same crystal, even though they may be individually and selectively retrieved, the color of the crystal is shared between the two recordings. Thus, if a strongly bleached region of one hologram coincides physically with an unbleached region of the second hologram, the contribution of the unbleached region to the second hologram read-out is removed. Correspondingly, as more and more holograms are superimposed in the same crystal there is greater and greater attrition of contrast in all of them, with consequent reduction in image brightness and quality.

The effect of exposure programming is related to the previous effect in the sense that the holograms stored earlier are reduced in quality and brightness to a greater degree than those stored later, assuming that complete utilization of available dynamic range by each hologram is not practiced, in the interest of conserving color density.

Some solutions to these difficulties are provided by a new recording technique, labelled RTX for Room-Temperature Exposure. This method is based on the discovery that red light at room temperature is more effective as a retarder of coloration than it is as a bleaching agent. Normally, ultraviolet light is employed at room temperature to color a bleached crystal preparatory to recording; with the new technique, recording with red light is carried out simultaneously with ultraviolet exposure. The red light, carrying the information, retards coloration by ultraviolet, thus recording the information at room temperature and avoiding the difficulties associated with heating and cooling the crystal mentioned above. The selection of optimum relative intensities of red and ultraviolet light should also lead to considerable improvement (if not a complete solution) to the bias build-up problem. The behavior of the crystal under this RTX technique is illustrated below.

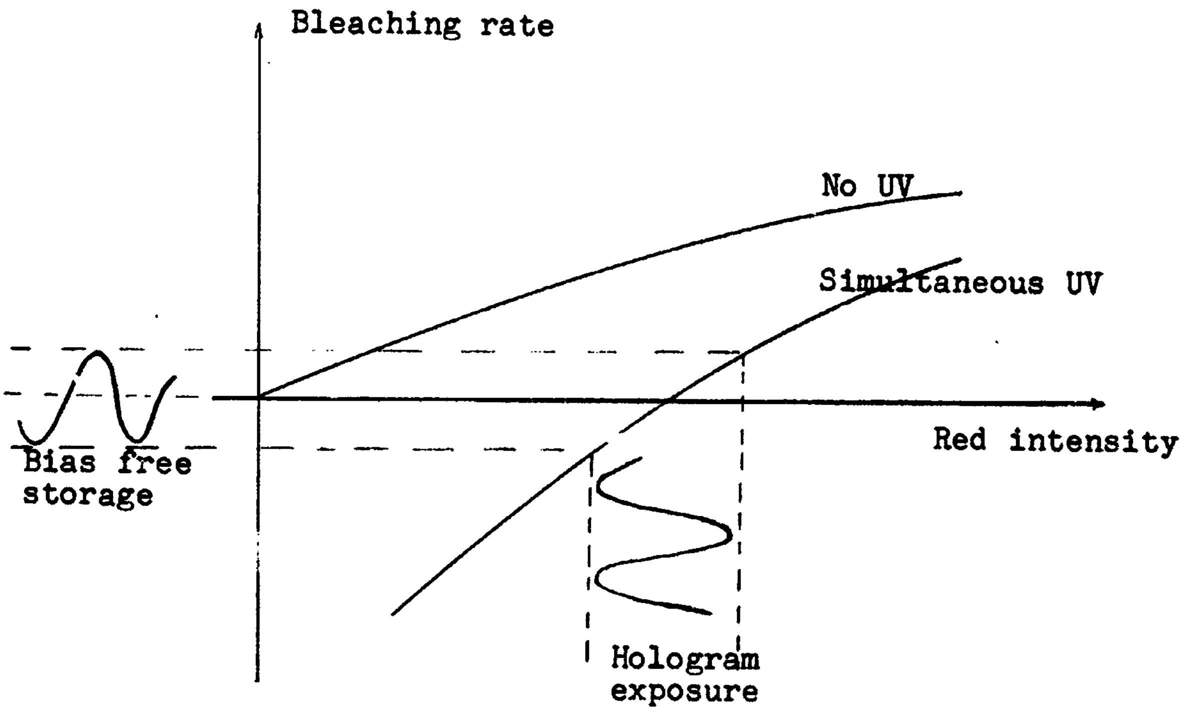


FIGURE 12. Bias-Free Counter Exposure Technique

In Infon k-space we can easily evaluate possible optimized configurations for maximum Bragg Angles. This concept is discussed more completely in the following section.

Some possible improved Bragg-capability configurations. Bragg selectivity is optimal when the internal angles are 90° between the information and the reference beams. Because of the index of refraction of the crystal, this would correspond to near-grazing entrance of light into the crystal. Three alternative arrangements are illustrated below which provide for ways to obtain the optimal 90° configuration without entering the crystal at grazing. The latter condition is clearly undesirable due to the very small angle available for storing multiple images as well as for increased scattering losses and noise at grazing incidence.

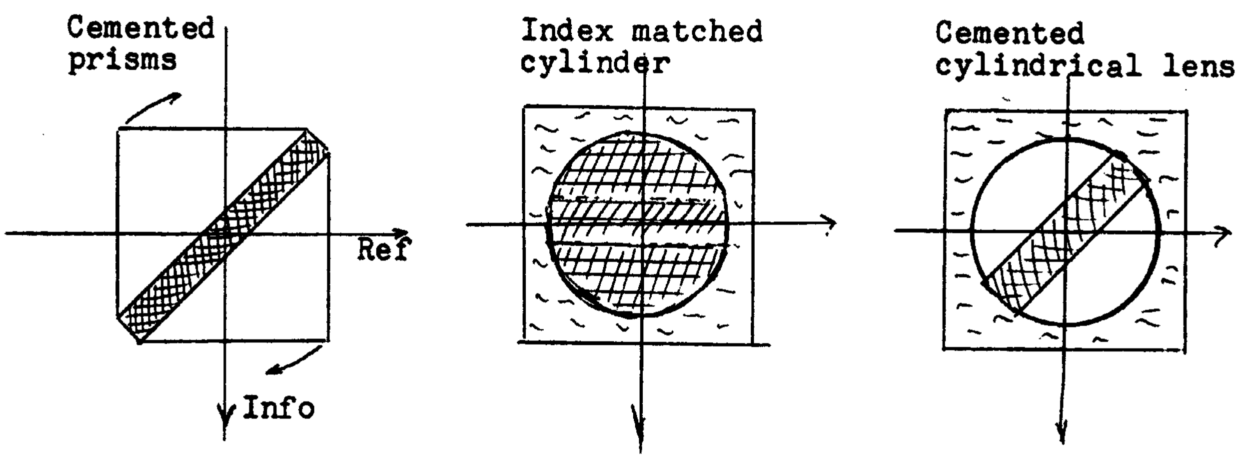


Figure 13. Three configurations that allow orthogonal internal angles. Dark areas represent the crystal.

THE INFON

The potential information storage capability of 10^{17} color center flip-flops per cubic centimeter staggers the imagination. The problems of realization, however, are great.

There is no way to address these centers individually; and in most cases there is no non-destructive read-out. In this system (just as in the case of the mechanical vibrations of a crystal lattice) it is not useful to speak of the behavior of a point of the lattice. The concept of a quantized plane wave, the phonon, helps describe the state of the mechanical system; analogously, the concept of a quantized plane wave of the color density helps describe the information content of Bragg holographic volume storage media. This is the concept of an infon.

Observable vs Visible Infons. An elementary fringe system is created in the crystal at the intersection of two coherent, monochromatic plane waves of propagation vectors $\bar{k}_i$ and $\bar{k}_r$. $\bar{k}_i \equiv \bar{k}$ information; $\bar{k}_r \equiv \bar{k}_{reference}$. $|\bar{k}_i| = |\bar{k}_r| = k = 2\pi/\lambda$. The wave vector of the holographic fringes is $\bar{K} = \bar{k}_i - \bar{k}_r$.

In $\bar{K}$ space, any point represents a fringe system. A fringe system is "observable" with a given color of light, $|\bar{k}_r|$, if

$$|\bar{K}| \leq |2\bar{k}_r|$$

i.e., if there is such a combination of k_r and k_i that they satisfy the above vector equation.

A fringe system is "visible" with a given directional $\bar{k}_r$ if $|\bar{K} \pm \bar{k}_r| = k$

Thus, all fringe systems that fall within a sphere of radius 2k are observable; and all fringe systems that lie on the surface of a sphere of radius k and centered at $\bar{k}_r$ are visible with that given reference beam.

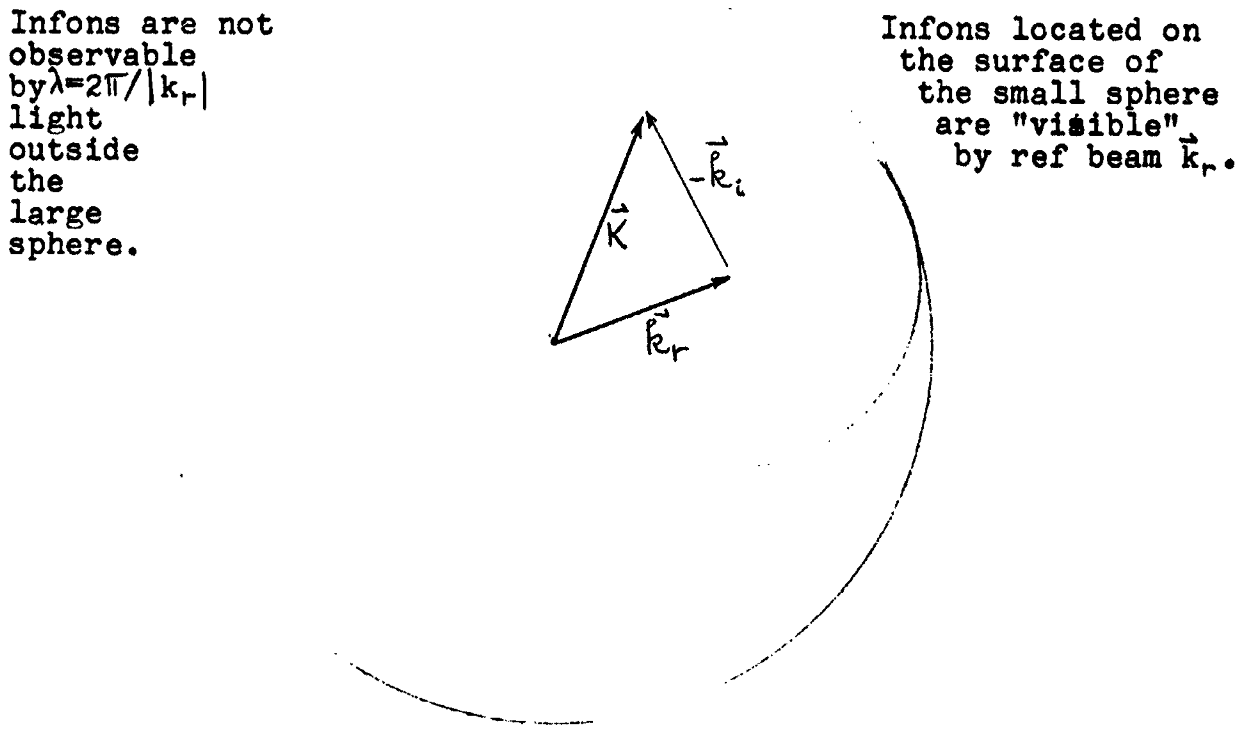


FIGURE 14. Observable and Visible Infons

<u>Quantization</u>. The infon becomes a well defined and useful concept only through proper quantization. We have to establish criteria of distinguishability. There are two types of small changes a fringe system can undergo.

1. Change in frequency, $\Delta\bar{K} \parallel \bar{K}$
2. Rotation, $\Delta\bar{K} \perp \bar{K}$.

A familiar result from grating and holographic theory is that two neighboring resolution elements differ by one in the number of fringes they contain in the length of the storage medium

$$a/\lambda_1 = a/\lambda_2 + 1, \quad \text{or}$$

$$K_1 = K_2 + 2\pi/a$$

i.e., $\Delta K = 2\pi/a$, where a is the linear dimension of the medium in the $\bar{K}$ direction.

An identical criterion is obtained for the rotation of the fringes. For two fringe systems to be distinguishable they must be rotated with respect to each other by just one fringe shift at the edge of the storage material. This yields similar criteria

$$\Delta K_y = 2\pi/b, \quad \text{and} \quad \Delta K_z = 2\pi/c.$$

An exact quantization can easily be done on a hypothetical Gaussian storage medium. Instead of sharp boundaries, which are bound to complicate the mathematics, this extends to infinity but with a decreasing weight. The storage medium is defined by

$$\exp\left[-\tfrac{1}{2}(x^2/\sigma_x{}^2 + y^2/\sigma_y{}^2 + z^2/\sigma_z{}^2)\right].$$

Here, σ_x, σ_y, σ_z define the "size" of the medium. We obtain a discrimination ellipsoid which is longest in the direction of the shortest dimension of the storage medium and vice versa.

Visibility must be redefined with this ellipsoid in mind. An infon $(\bar{K})$ is visible by a reference beam, $\bar{k}_r$, if there is such a $\bar{k}_i$ that $\bar{k}_r - \bar{k}_i$ falls within the quantum cell of $\bar{K}$.

A large discrimination ellipsoid allows read-out even though $|\vec{K} \pm \vec{k}_r| \neq k$

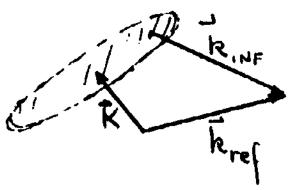
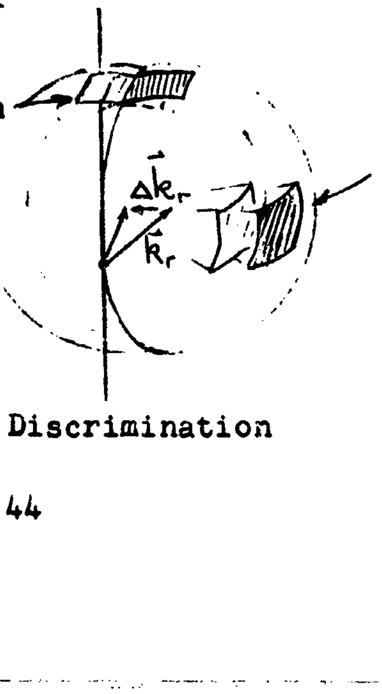


FIGURE 15. A Visible Infon

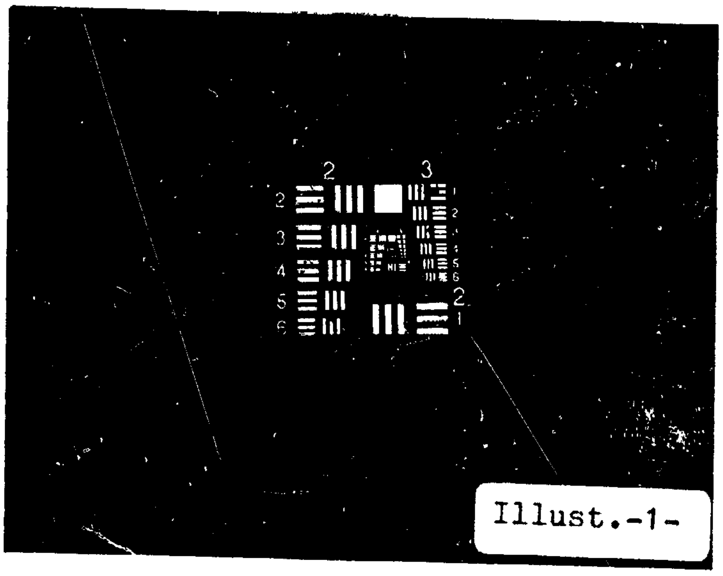
<u>Bragg Discrimination vs Resolution</u>. Resolution concerns the nature of quantization on the sphere of simultaneously visible infons; Bragg discrimination describes the quantization of neighboring spheres. Not all parts of the sphere undergo Bragg discrimination. As the sphere makes an incremental motion, corresponding to a changed readout beam, there is a near-great-circle of intersection. At and near this circle there is no discrimination. $(\Delta\bar{k}_r \perp \bar{k}_i)$. The most critical Bragg selection is near the parts of the sphere which are in the direction of motion. $(\Delta\bar{k}_r \parallel \bar{k}_i)$.

Poor discrimination



Area of good Bragg discrimination.

FIGURE 16. Bragg Discrimination



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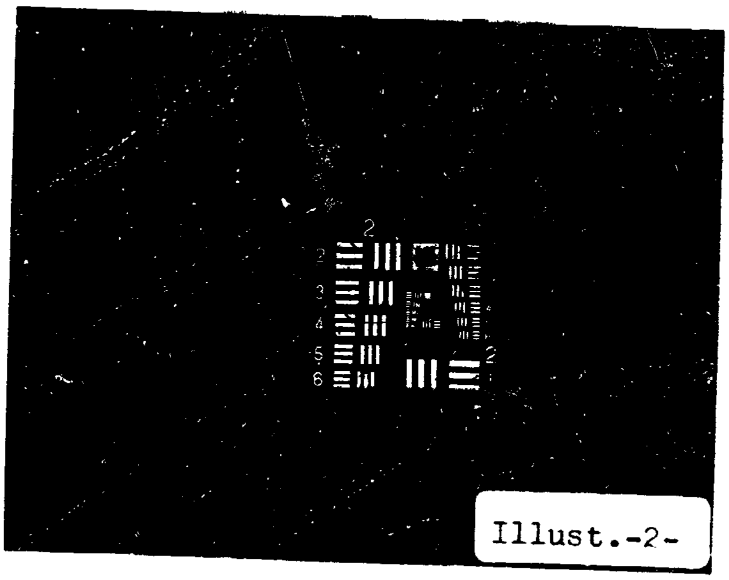

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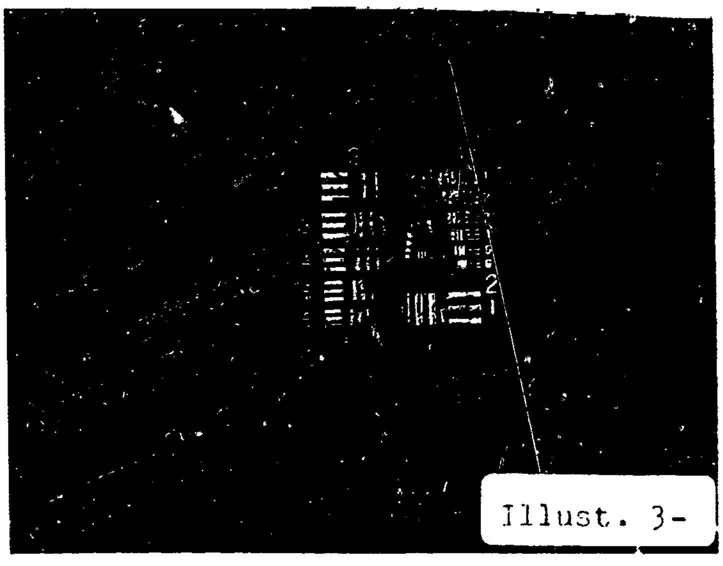

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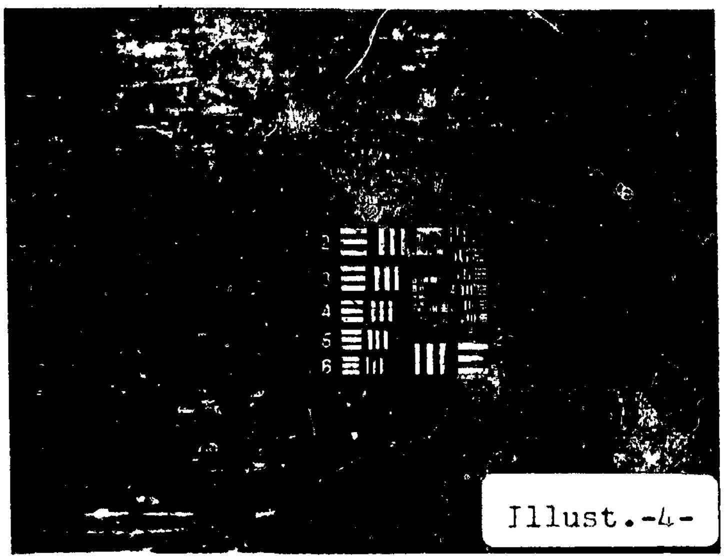

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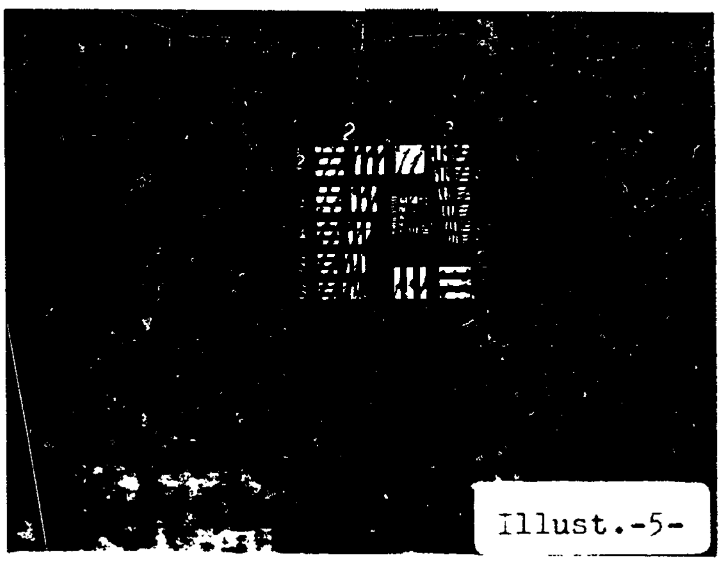

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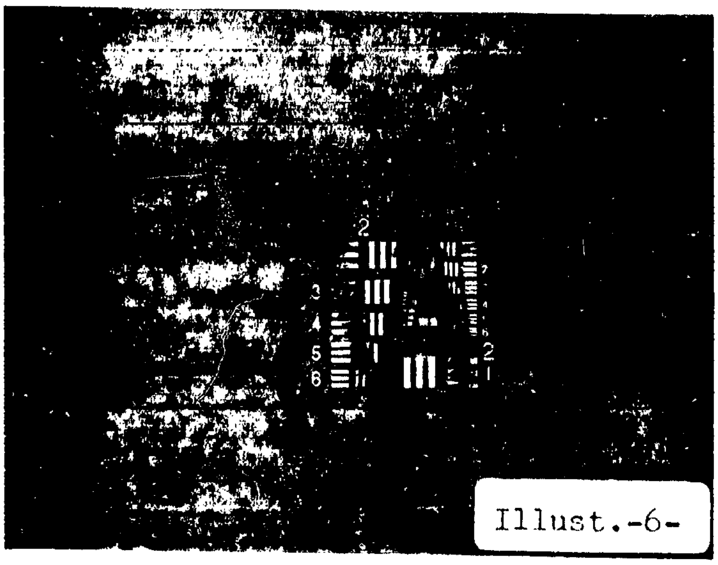

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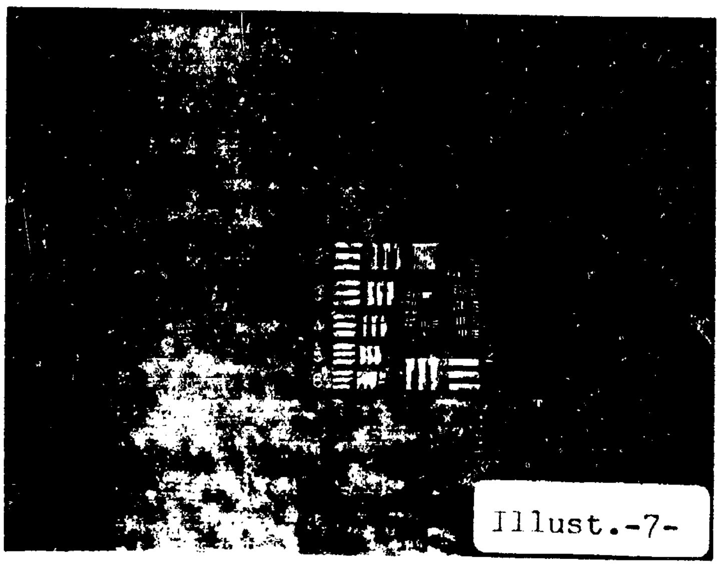

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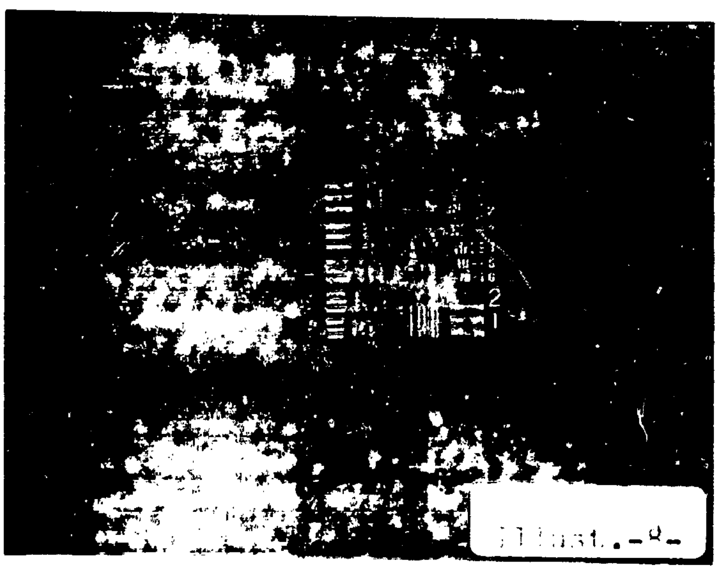

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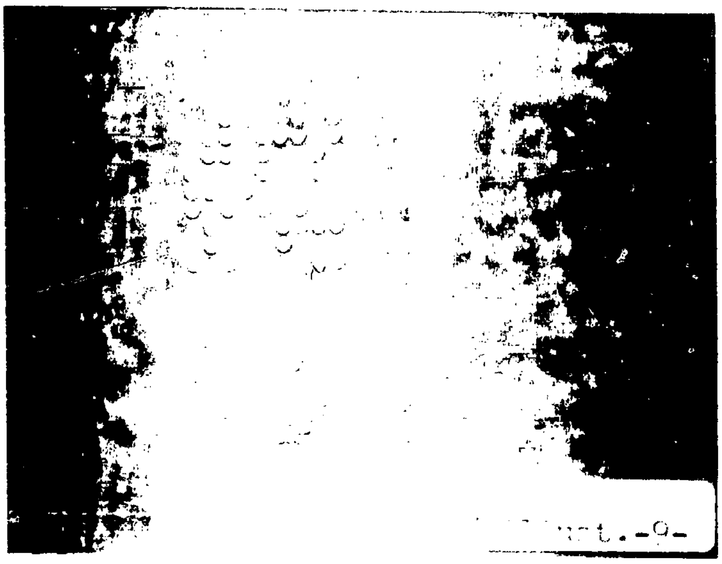

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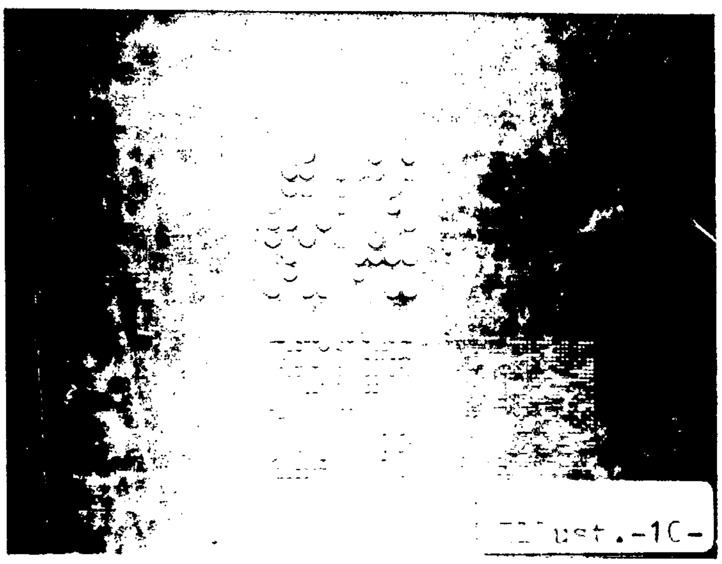

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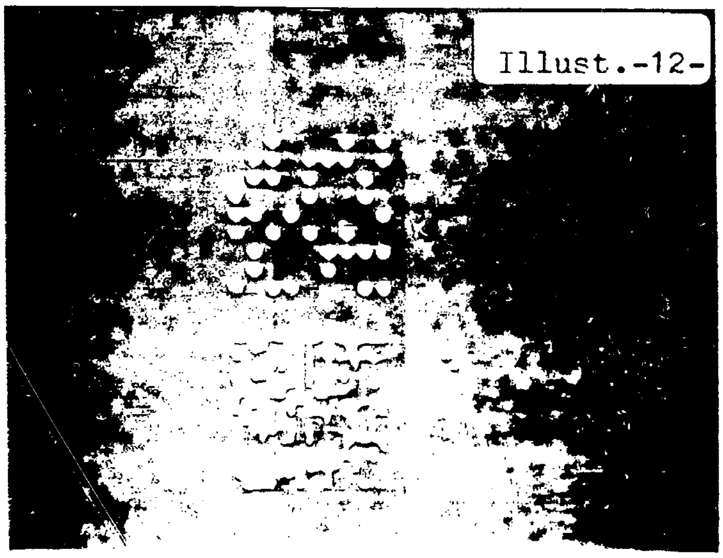

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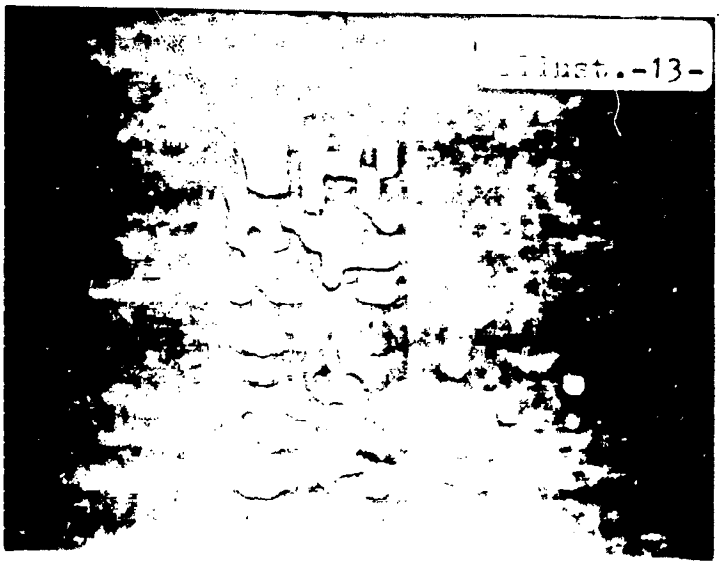

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